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Periodicity Trees in a Secondary Criterion of Periodic Classification: Its Implications for Science Teaching and Communication

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Abstract. In this work, I will present a proposal for introductory courses in chemistry. After the topics of atomic structure, chemical periodicity and chemical bonding, this proposal addresses the study of the periodic system based on triads, which has closed structures called periodicity trees as a secondary periodic criterion. This table was designed from a classical chemical perspective, with the purpose of integrating traditional topics and of supplying a conceptual basis for new ones, and, mainly, to privilege the chemical over the physical approach in the process of teaching-learning chemistry in initial courses.

Keywords. Periodicity tree, chemical element, periodic system, teaching and communication in chemistry.

No sólo le costaba comprender que el símbolo genérico "perro" abarcara tantos individuos dispares de diversos tamaños y diversa forma; le molestaba que el "perro" de las tres y catorce (visto de perfil) tuviera el mismo nombre que el "perro" de las tres y cuarto (visto de frente).[1]
Jorge Luis Borges

1. INTRODUCTION

Borges's quote, presented as an epigraph, is included in the short story "Funes, his memory", and serves as a trigger to the purpose of this work: Not only was it difficult for him to see that the generic symbol "dog" took in all the dissimilar individuals of all shapes and sizes, it irritated him that the "dog" of three-fourteen in the afternoon, seen in profile, should be indicated by the same noun as the dog of three-fifteen, seen frontally.[2]

Just as the generic symbol 'dog' comprises many different individuals, of various sizes and diverse forms, the generic symbol 'chemical element' comprises a multiplicity of species in the same locker of the periodic tables. For example, one box of the usual periodic tables includes all the isotopes of an element, all the simple ions of all the isotopes of that element, all the ions combined to each other, and therefore all the isotopes of all the elements that make up each combined ion, in turn, in all possible combinations. It furthermore also encompasses all the molecules, from the simplest that the element can form, as oxides or hydrides, going through those of more complex structures, like most organic molecules, to all polymers, both natural and synthetic, in which that element can be part of, etc.[3] In addition, a single locker includes all those species in all possible contexts in which they can be presented, for example, solutions with subtle variations in concentration or pH. The context, although usually neglected, is a however fundamental aspect in chemistry, since small variations, which can be considered insignificant –as the difference between *the dog of three fourteen (seen from the side) with the dog of three fifteen (seen from the front)*– may induce large changes in some particular reactions such as the case of saturated solutions or metastable systems.

Ireneo Funes, the character of Borges's short story, found it hard to comprehend that the generic symbol 'dog' covers many different individuals in size and in shape. By contrast, most students of initial chemistry courses experience no difficulty to approach the complexity of the concept of chemical element, as they simply do not become aware of that complexity, of that conceptual labyrinth. To them, the concept of element coincides with the concept of atom, and an atom is a cluster of protons and neutrons in the nucleus and electrons in the periphery, which are organized in a "quasi-military" way in "decreed" energy levels; in turn, molecules are simply conceived as sums of atoms. The purpose of this contribution is to present an alternative view that could be used in the educational context, in order to help the student to become aware of the complexity involved in the term 'chemical element', and of the importance and limitations of the periodic classification of elements. The acknowledgement of the complexity of this problem and of all the problems derived from the concept of element – basically all chemistry –, far from discouraging the students, should stimulate them to approach the exciting task of studying chemistry.

Let us recall that the standard periodic table (SPT) is organized by a primary criterion, which orders the elements by increasing atomic number, and a secondary criterion, which allows grouping elements in chemically similar families according to the electronic configuration of the last layer. In contrast we suggest the following alternative. After teaching the initial topics of the regular course – atomic structure, periodic table and chemical bonding, the table based on atomic number triads (hereafter called TBT, Table Based on Triads) is introduced, in order to integrate those topics from a purely chemical perspective.[4] The TBT maintains the primary criterion but, as a secondary criterion, it proposes to organize the elements in a series of closed structures called 'periodicity trees' (pT's). The peculiarity of this periodic table is to dispense with all consideration of electronic configurations. This is a fundamental point of the proposal, since it shows an alternative way of organizing the elements without using a concept that, although it is very relevant in chemistry, comes from a physical theory as quantum mechanics.[5,6] Moreover, this approach shakes two common "beliefs" by showing, on the one hand, that the concept of element is not as simple as usually believed, and, on the other hand, that classifications are never unique: there are very different ways of classifying, each useful in its own field or application. In the case of TBT, the secondary criterion of classification is periodicity tree (pT), which focuses on the classification of the elements from a chemical and non-physical perspective: the criterion is based on macroscopic chemical similarities among elements and not on quantum features of atoms (see Sections 4 and 5).

With this goal in sight, the article is structured as follows. The next section provides a brief historical overview on the development of the concept of element. Section 3 sketches the path towards periodic classification. Section 4 describes the proposal of the periodic system based on triads (TBT). By section 5 we will be described focusing on the structures called 'periodicity trees' (pT). Section 6 will introduce the implications in the context of teaching and communication of chemistry; in this section the main proposal of this work will be explained and the treatment of some relevant issues in this context will be discussed. Finally, the conclusions of this work will be presented.

2. THE ROOTS OF THE NOTION OF ELEMENT

From pre-Socratic philosophy to modern times, the concept of element was mainly philosophical, designing the originating principle of everything real: it referred to what is primary, fundamental and persistent, in opposition to what is secondary, derivative and transitory. It was only in the eighteenth century that Antoine Lavoisier (1743-1794) proposed an operational definition of element that had a strong influence up to now: elements are the ultimate product of chemical analysis.

Dimitri Mendeleev (1834-1907) replaced the Lavoisier program, based on the relationship between simple body and compound, by the relationship between element and simple or composite body.[7] Simple body ceases to be an explanatory principle and becomes an appearance. Only elements, hidden in simple and composite bodies and remaining in spite of change, can be an explanatory principle. This motion from the concrete reality of simple bodies to the abstract reality of elements, is what allowed Mendeleev to conceive a general system of elements that goes far beyond a mere grouping of chemical families.[8]

With the advent of quantum physics in the early twentieth century, the atomic theory pervades the field of chemistry, and the concept of element is assimilated to that of atom. However, after the discovery of isotopes by Frederick Soddy (1877-1956) in 1913, elements seemed to "multiply" and the doubts about whether or not there were new elements triggered what Eric Scerri calls as the "periodic table crisis".[9] It is in the context of this crisis that Friedrich Paneth (1887-1958), in 1931 proposes the dual nature of the concept of element, distinguishing between elements as *simple substances* according to their phenomenological manifestations, and elements considered in an abstract sense as *basic substances*, whose only property was no longer their atomic weight, as in Mendeleev's, but their atomic number, in consonance with the new quantum mechanics.[10] For Paneth simple and basic substances are not two descriptions of the same entity, product of an epistemic limitation to be overcome in the future; for him, the very concept of chemical element embodies a double nature. The epistemological status of the basic substance is part of the current discussions about the nature of the concept of element among historians, chemists, educators and philosophers of chemistry. These discussions show that, although there is a broad consensus about the extension of the concept, there are strong disagreements with respect to its intention (cf., for example, Bent, Hendry, Schwarz, Earley, Ruthenberg, Scerri).[11,12,13,14,15,16.]

3. THE ROAD TOWARD A PERIODIC CLASSIFICATION

According to Van Spronsen and Scerri, two notions led to the evolution of the periodic system: the Prout hypothesis and the Döbereiner triads.[17,18] The idea that all simple bodies must derive from hydrogen was formulated by the Scottish physicist William Prout (1785-1850), who noted that many of the atomic weights determined for the elements were integer multiples of the atomic weight of hydrogen. Prout concluded that hydrogen could be the fundamental element, and that all other elements would be formed from this element by a condensation phenomenon. This hypothesis implied that all the elements had to have whole atomic weights, which was in contradiction with many experimental data of the time. Prout's hypothesis played a double role in the history of the classification of the elements: on the one hand, it stimulated research aimed at the exact determination of atomic weights, and on the other hand, it also weakened the tendency to systematize the elements through its phenomenological properties, imposing the primacy of classification by atomic weight.[15]

In 1817 the German chemist Johann Wolfgang Döbereiner (1786-1849) reported that certain elements associated in groups of three, presented chemical similarity and a particular arithmetic relationship: the atomic weight (or equivalent weight) of the second element was almost exactly the average of the other two. He called these groups '*triads*'. For instance, Döbereiner found that selenium in the triad of sulfur, selenium, and tellurium had an atomic weight that was the approximate average of the weights of the other two elements. The importance of this discovery lies in the association of qualitative chemical properties, such as the kind and the degree of reactivity, with numerical properties of the elements. This suggested that there could be some underlying numerical order that could serve to relate the elements to each other in a systematic way. Döbereiner also discovered other triads, such as calcium, strontium and barium, and lithium, sodium and potassium. Other chemists discovered still more triads and began to elaborate tables that tried to relate the triads to each other.[15]

Among the precursors of the periodic system, William Odling (1829-1921) classified the then 45 known elements into 13 groups.[19] Also noteworthy is the contribution made by the British chemist John Newlands (1837-1898), who in 1864 published a table of 24 elements subdivided into five groups.[20] He noticed that in the table there was a repetition of some properties of the elements every certain regular interval. Then he placed the elements in increasing order of atomic weights, giving each one an order number. In 1865 he published another table containing the numbered elements arranged in eight columns.[21] He observed that when counting from any element, the eighth had similar properties. He called this relationship "the law of octaves". In turn, in 1864 the German chemist Julius Lothar Meyer (1830-1895) presented a table of 28 elements, arranged horizontally according to their valence (see also Boeck's article on Meyer in this special issue).[22,23] In 1868 he proposes another periodic table with the atomic weight as criterion of order. This new table had 55 elements arranged vertically in 15 columns, being classified in families located horizontally.[24] By then clearly the ordering of the elements was linked to the atomic weights and the analogy in their chemical behavior, which went beyond Döbereiner's concept of triads but definitely built on it.

When he had to dictate his chemistry course, Mendeleev considered that he lacked appropriate teaching material and decided, like many of his colleagues, to develop his own manual.[25,26] One of the first difficulties that he found was how to organize the huge set of chemical knowledge, accumulated over decades, about thousands of known chemical substances. From the time of Lavoisier, the mostly adopted solution for teaching consisted in relating the properties of a composite substance with the properties of its component *simple* substances.

By contrast, Mendeleev adopted a pluralist position. From his perspective, phenomenal properties are nothing else than external manifestations of more abstract entities, the elements: he considered that elements had a more fundamental status, of a metaphysical nature, and that their only attribute is atomic weight. In this way, Mendeleev introduced a clear differentiation between simple body or simple substance and element. The notion of simple body or substance, which from Lavoisier had become the key concept of chemistry, is thus replaced by that of element, understood in an abstract or metaphysical sense. According to Mendeleev, the simple body is something material, and remains relegated to the world of appearances. The element is the only explanatory principle, the substratum of everything observable. The elements have no phenomenal existence, they are always "hidden" in a simple or compound body. It is that "something" that is conserved in chemical reactions. It is a fundamental reality, clearly abstract, which explains the conservation and permanence of individual properties despite chemical changes.[5]

Mendeleev was a strong defender of the individuality of the chemical elements, and therefore, a critic hostile to the hypothesis of Prout, which he considered contrary to the periodic law. It is on the basis of this conception of element that Mendeleev organized his classification endeavor; reaching that level of abstraction appeared was indeed an essential requirement for a successful classification. He was then able to consider that the properties of simple and compound bodies came as a periodic function of the atomic weights of the elements.[5]

The periodic classification marked the apogee of a chemistry centered on the elements: it recapitulated the facts, organized the laws, systematized the acquired knowledge and motivated the program of the theoretical development of chemistry from the notion of element. It was not the isolated discovery of an isolated individual, endowed with enough knowledge to be in the scientific vanguard of his time; on the contrary, it was the answer to a specific problem of nineteenth-century chemistry, and the culmination of a long history marked by evidence and errors.[5]

In the second decade of the twentieth century, the British physicist Henry Moseley (1887-1915) conducted experiments with discharge tubes, in which the rays collided with metal sheets of different elements. Moseley found that the X-ray spectra so obtained depended on the used metal, and that the lines of the spectra changed uniformly, maintaining a harmonic pattern, when moving from one element to the next of the periodic classification.[27] From his work, a new property was defined: the *atomic number*.[28,29]

In 1913, Niels Bohr (1885-1962) postulated a new atomic model for the hydrogen atom, based on the first quantum theories. Later, other researchers such as Arnold Sommerfeld (1868-1951), Pieter Zeemann (1865-1943) and Wolfgang Pauli (1900-1958) developed the theory and formulated the quantum numbers. The atomic model of Bohr, initially proposed for monoelectronic atoms, was then generalized to any multielectronic atom and the arrangement of electrons in these systems began to be studied, giving rise to the concept of *electronic configuration*, in whose development was fundamental the contribution of other scientists, mainly Charles Bury (1890-1968).[29] It is noteworthy that Bohr's approach was not based on any mathematical basis, nor explicitly resorted to quantum theory to assign the electrons in the different shells, but was guided by the chemical characteristics of the elements to assign them electronic configurations.[14,15]

Chemists accepted the Bohr model, because it provided a surprisingly intuitive version of the concept of atomic number, which indicated the position of the element in the periodic system. This number is equal to the number of electrons, and also to the number of positive charges that characterize the nucleus. Each successive element in the usual periodic table has one more electron that its predecessor, and the periodic changes of the valence observed in the table could be explained by the successive occupation of the orbits. In this way, a research program was initiated, which erased the traditional boundaries between chemical reactions and physical interactions.[31] The present way of teaching chemistry is the consequence of that program.

4. THE PERIODIC SYSTEM BASED ON TRIADS OF ATOMIC NUMBER[32]

As shown in the previous section, one of the early systematisation from which the periodic system was built was the concept of triad concept proposed by

Döbereiner; we regard the concept of triad as one of the pilar of the periodic system. At the beginning of the current century, Eric Scerri reformulated the concept of the triad, by defining them as based on atomic numbers; so, triads resulted from integer numbers.[33,34] Scerri also suggested the use of triads of atomic numbers as a possible secondary criterion for the periodic system. Although in the SPT (and in the representations directly derived from it) there is a large number of triads –which can be increased with the displacement of hydrogen to the group of halogens–, the formation of triads cannot be considered as a secondary criterion of periodic classification since it does not relate systematically to all elements.

In TBT, the primary criterion is given by the increasing atomic numbers, and the secondary criterion is established by the formation of triads of atomic numbers, which in turn form closed structures of 20 elements called 'periodicity trees' (pT's). The representation is based on three factors that act as criteria for the construction of the table: the conception of the elements in their character of basic substances, the triads of atomic numbers, and the chemical information on the behavior of the elements as simple substances.[3]

The fact that the three elements necessarily have similar macroscopic properties is no longer required in TBT, as was the case with Döbereiner. For instance, two of the elements of the triad may belong to consecutive periods with the same length, that is, of the same block, while the third may come from a different block, and thus belongs to a period of different length. In this approach, the elements of the same block have similar chemical properties, and the third element, also called "connecting element", performs the function of linking consecutive blocks. The idea of connecting element only makes sense when elements are considered as basic substances. The branches in the pT's are formed by those connecting elements (see the next section). This way of conceiving triads shows that chemical elements can be organized without appealing to electronic configurations, and without relying exclusively on the macroscopic properties of simple substances. Chemical periodicity can be characterized in a formal and abstract way, but, at the same time, it turns out to be compatible with the empirical knowledge accumulated in chemical experience. This proposal is inspired in the conciliation between the conceptions of element as basic and simple substance, in the sense recommended by Scerri: "Paneth's insistence that the periodic system only classifies elements as basic substances invites the obvious question of how we might learn about these elements, especially as they are said to have no properties. Admittedly atomic number provides an ordering criterion but periodic classification is also about group similarities which are recognized through the properties of elements as both simple substances and as combined simple substances. It is difficult to see how focusing on elements as 'basic substances' can provide any indication of the second dimension of the periodic table, namely the grouping of elements into vertical columns.[35]

In the proposal of TBT, elements are grouped so that all are involved in at least one triad; it is for this reason that formation of triads can be adequately considered as the basis of a secondary classification criterion. The table is structured as follows: (i) periods result from organizing the elements according to the increase in atomic number; (ii) in each period, a new generation of triads is formed, and each generation will have as many triads as the period has (see Figure 1, where all the triads are shown).[3]

The fist 8 periods contain: 1, 1, 8, 8, 18, 18, 32 and 32 elements, respectively. If the series were extrapolated for the construction of the table, the ninth period should contain 50 elements. However, due to anomalies in some elements of the eigth period, a reversal of the sequence is proposed.[3]

Finally, it is interesting to notice that the TPT preserves several aspects present in the Mendeleev classification: the abstract perspective on the nature of elements to allow the structure that classifies them, and also the individuality of the chemical elements as a fundamental and objective feature of nature.

5. PERIODICITY TREES

The system introduced in the previous section is based on the idea that triads manifest the abstract relations between elements, which only make sense at the level of basic substances, but not necessarily in that of simple substances. Thus, each triad in this system should not be thought of individually, but within a pT, that is, a set of nested triads. In other words, each triad is conceived as a part of a tree, in such a way that it becomes meaningful only within this set of relationships. The concept of pT is proposed as an alternative to the traditional concept of group in the SPT.[36]

A pT is a symmetric structure where the elements are related by triads: there are 9 structures of this type (see Figure 2). Since they make up the architecture of the table, they manifest the secondary criterion of classification in TBT.

There are two types of pT: 8 lateral trees of 20 elements, and a central tree also of 20 elements, which is

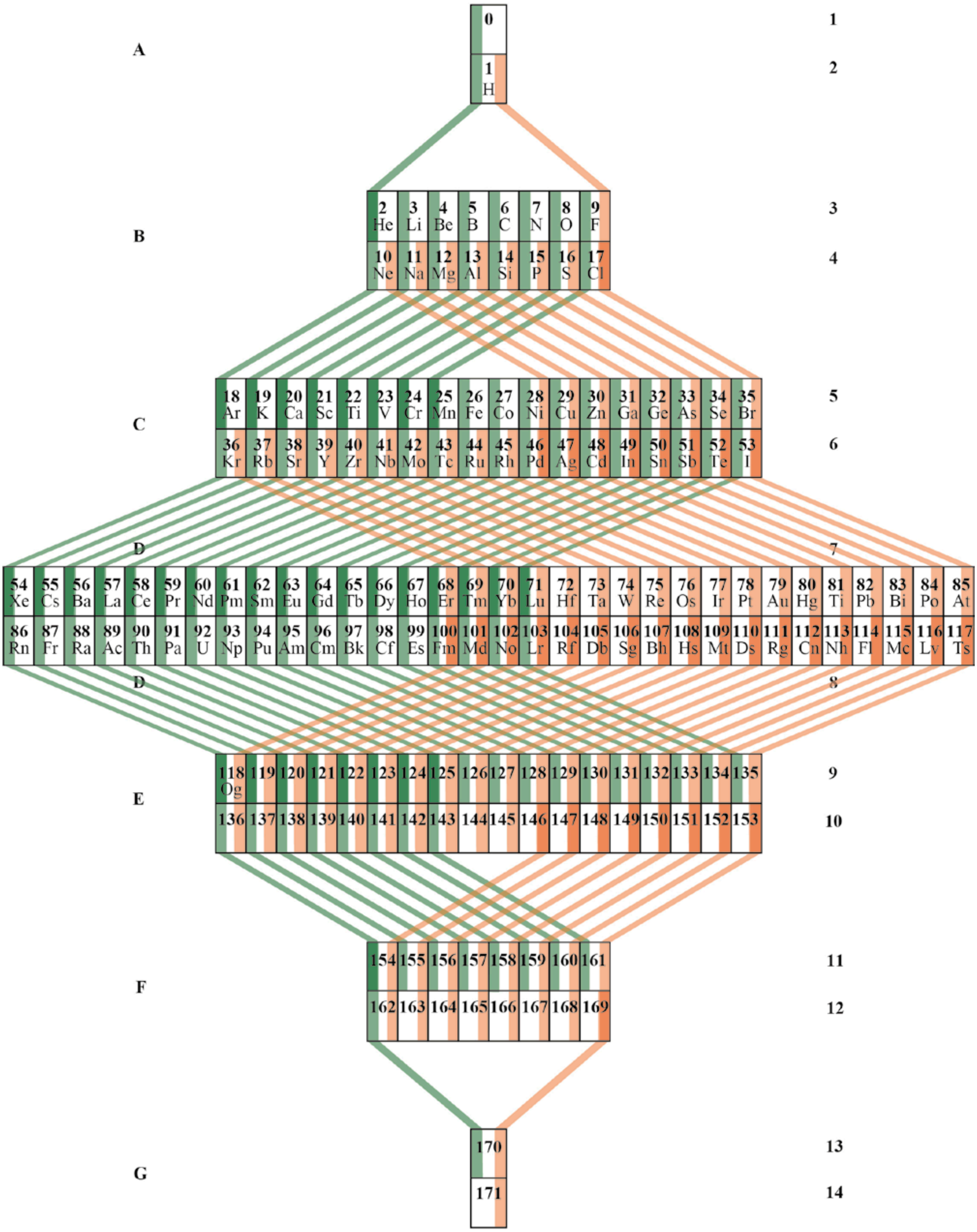

Figure 1. Periodic table bases in triads: in green the triads corresponding to even generations, in orange those corresponding to odd generations. Observe that in each period, a new generation of triads is formed.

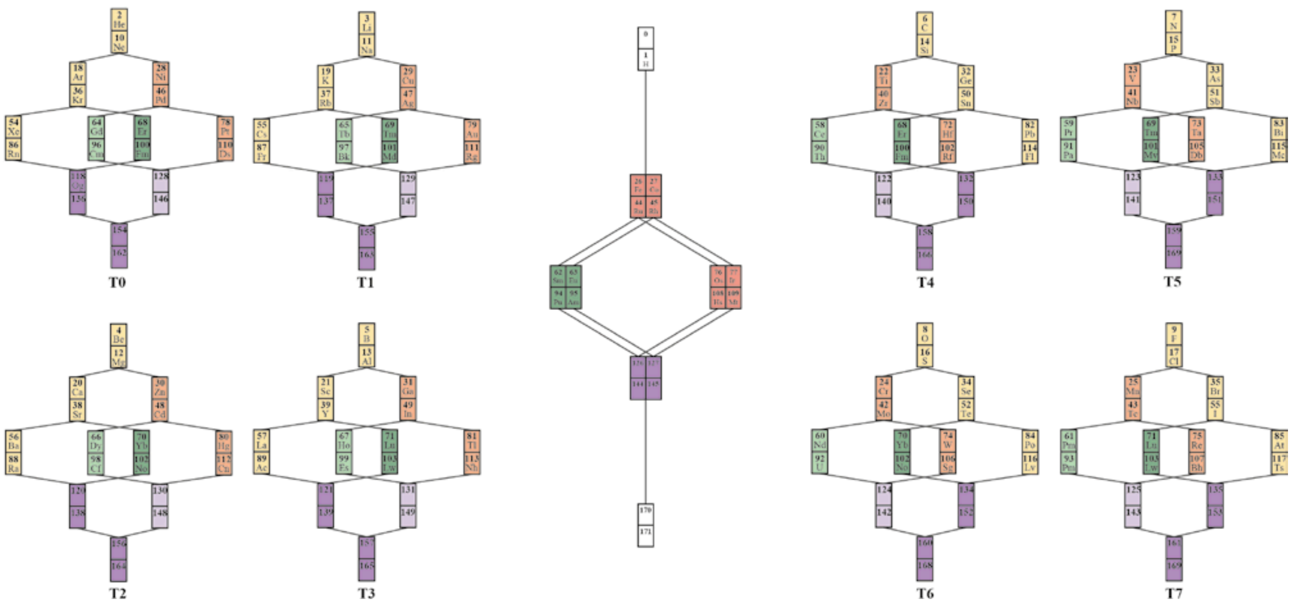

Figure 2. The nine periodicity trees make up the TBT.

formed from the elements not included in the lateral pT's. The *main branch* is the branch that starts with the first two elements and continues with those located at the left in the first 4 trees, and the branch that starts with the first two elements and continues with those located at the right in the second 4 trees. The opposite *complementary branch* is the yellow branch in the first 4 trees, and the orange branch in the second 4 trees (see Figure 2).

The 8 lateral pT's include, as their first element, those elements that start the representative groups of the series A (with the exception of hydrogen, which is a very special element, see next section). Each one of them contains 20 elements, connected through a succession of concatenated triads. In order to give an idea of the structure of the pT's, let us consider the features of the lateral tree T1 and of the central tree.[3]

The tree T0 begins with the triad 2-10-18 (He-Ne-Ar). Then, it continues to the right with the triad 10-28-46 (Ne-Ni-Pd), where Ne acts as a connector element where the first bifurcation occurs. Then, the triads 18-36-54 (Ar-Kr-Xe) and 28-46-64 (Ni-Pd-Gd) follow in the construction. In this way, in the laterals of the tree, the group VIII A of the noble gases appears as a left main branch, and the third column of group VIII B of the STP appears as a right complementary branch in the same structure.[37]

In turn, in the one of the central branches of the tree, the first lanthanide (Gd) is included, in the next generation the triads 36-68-100 (Kr-Er-Fm) and 46-78-110 (Pd-Gd-Cm). The first actinides (Fm and Cm), and the second lanthanide (Er) appear. The next generation is composed of the triads 54-86-118 (Xe-Rn-Og) and 64-96-128 (Kr-Er-Fm), which complete the elements known up to the present in T0. The tree continues with triads formed some hypothetical elements: the triads 100-118-136 (Fm-Og-136) and 96-128-146 (Cm-128-146), then the triad 118-136-154 (Og-136-154) comes, and finally the triad 146-154-162 which closes the tree.[3]

The pT's T1 to T7 are constructed by following the same procedure, by adding 1 to the number of each element. In turn, the central pT includes the elements not contained in the lateral pT's, beginning by 26 and 27 (Fe and Co). The central tree allows to reconstruct the first 2 columns of the SPT by means of triads. The central tree also includes the first 2 elements (0 and 1) and the last 2 (170 and 171).[3] Figure 3 shows the complete TBT.

6. IMPLICATIONS FOR THE TEACHING AND COMMUNICATION OF CHEMISTRY

In higher secondary education and university courses of chemistry of introductory level, the teaching of the periodic relationships among chemical elements generally follows the study of the electronic structure of atoms and precedes the basic concepts of chemical bond. In this way, the most frequent strategy (without considering the different possible approaches whose analysis is not the purpose of the present work) begins by study-

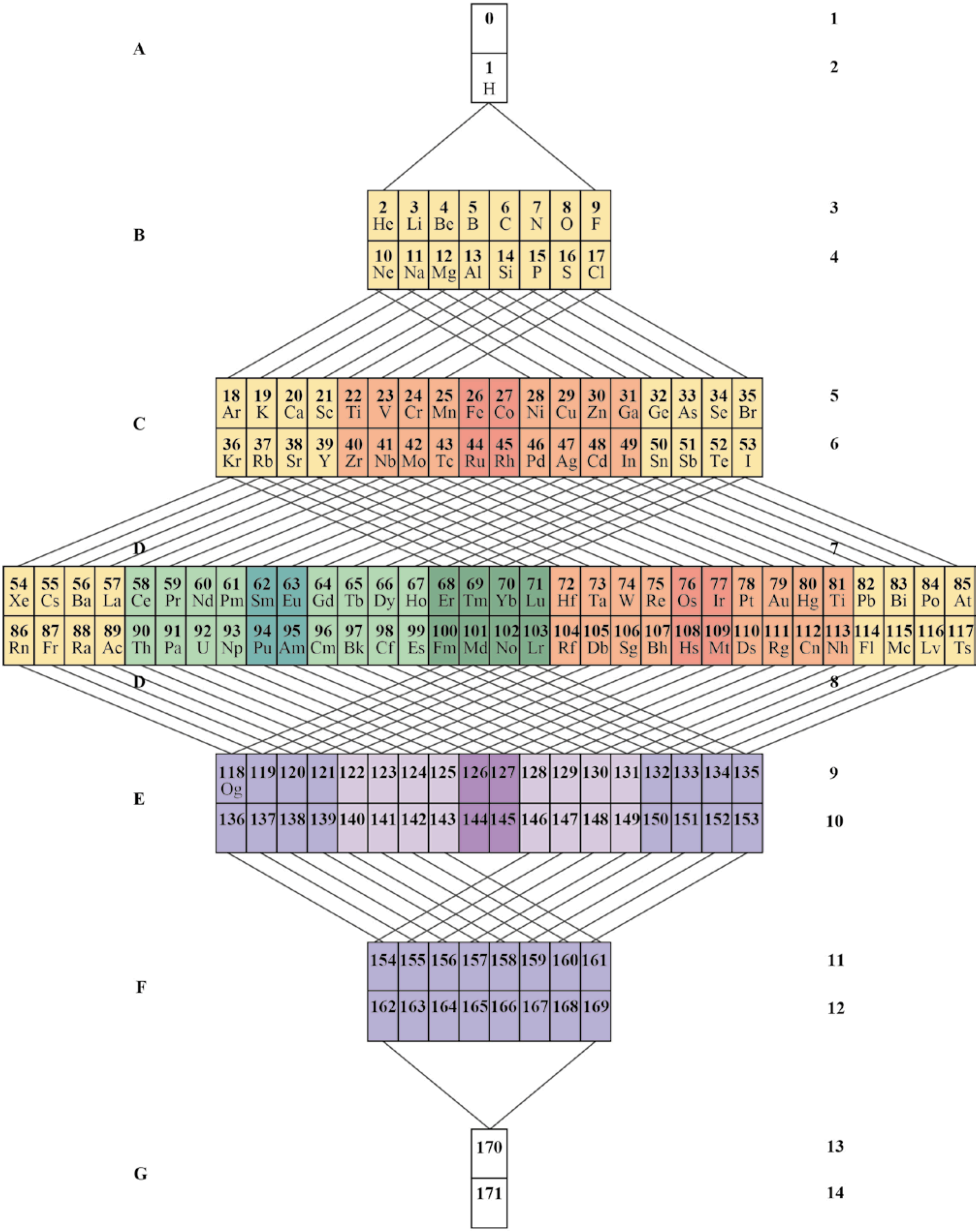

Figure 3. Periodic table based in triads, in the same color the elements that must present relations of periodicity.

ing the electromagnetic radiation and the atom from the quantum-mechanical point of view, on the basis of the uncertainty principle, an introduction to the wave functions, the quantum numbers and the characteristics of the atomic orbitals. Then, the chemical periodicity is approached from the point of view of the quantum numbers and the electronic configurations of the neutral atoms, the electronic configurations of the ions, and the variation of the periodic properties, such as ionization energy, electronic affinity, and atomic and ionic radio. After this, covalent and ionic bonds, the rule of the octet and its exceptions, the Lewis structures, the load distribution, and the formal charge are introduced. Finally, the theory of repulsion of valence orbitals and an introduction to the theory of molecular orbitals are explained.[38]

This way of presenting the topics in chemistry courses is the result of the uncritical acceptance, by most of the current chemical community, of the quantum tools as potential solutions and comprehensive explanations of all the problems and challenges posed by chemistry. This, in turn, derives from the great influence of the so-called "dictum" of Dirac: "The fundamental physical laws necessary for the mathematical theory of a large part of physics and the totality of chemistry [are] completely known from quantum mechanics."[38] In recent years, many works in the field of the philosophy of chemistry addressed the problem of reduction, focusing on logical, ontological, epistemological and historical aspects and questioning the validity of Dirac's dictum. The present work is part of this trend: it is based on the assimilation of new philosophical research, or rather, the part of that new research that is relevant to chemistry.[40]

From this perspective, I propose, as a didactic strategy, to teach the periodic system on the basis of TBT and the concept of pT, immediately after the treatment of the notions of atomic structure, chemical periodicity and chemical bond.[41] It is important to introduce TBT after chemical bond, and not in conjunction with the standard study of chemical periodicity, in order to emphasize the chemical approach over the physical one. This table can be used as a tool to integrate the preceding topics, and in this way to consolidate their conceptual bases; this facilitates the approach to the later topics with a fundamentally chemical approach, and not, as usually happens, from a physical perspective.

The TBT, given its foundations, might have been contemporary to the Lewis's proposals at the first decades of the last century, since it is conceptually independent of the quantum-mechanical description of the atom. In fact, for the elaboration of TBT, I relied on a *deliberate anachronism*, by "rewriting" the periodic system with an approach that rescues the essential aspects of the chemical perspective of the late nineteenth and early twentieth centuries. At that time, chemistry boasted of being an active, autonomous, and academic science, self-reliant.[42]

On this basis, I tried to accommodate the later developments of the discipline from a chemical perspective, that is, from a classical way of understanding chemistry. This view does not intend in any way to conflict with the quantum perspective, whose study is fundamental especially for university students of chemical-based careers. The aim here is to complement and enrich that physical point of view, and to reassess the chemical approach over the physical for the process of learning chemistry in the initial courses. The concepts and aspects that can be enriched by this proposal are: (1) the concept of chemical element; (2) the concept of "valence shell" and, in a certain sense, also the treatment of the notion of electronic configuration; (3) the relations between the groups of the series A and B of the SPT, which appear naturally in the pT's; 4) the concept of metal element; (5) the debate about the elements difficult to be classified according to the standard view; and (6) some considerations on the foundations of the periodic system under discussion. While the latter issues are still debated among specialists, the four first are integral to the teaching of chemistry from the secondary school on. I will expand briefly on each of them in the subsequent sub-sections.

6.1 The concept of chemical element

It is very common that students, especially in the initial courses of chemistry, but also in the advanced courses, consider the concept of element as equivalent to the concept of atom.[43] The concept of element is even introduced in terms of its electronic configuration, as if there were almost nothing else than electronic configuration as relevant for chemistry. Every element is usually represented in terms of the closest noble gas, to which the missing part of the electronic configuration is added. Thus the chlorine element, for example, is usually represented as [Ne] $3s^2$ $3p^5$. More than an individual entity, a chemical element is considered the result of the sum of elementary particles, which in some sense (perhaps not too indirect) implies an allegorical return to the hypothesis of Prout. This view equates the concept of the element to that of the atom, and the concept of molecule to that of a simple set of atoms; chemistry is thus understood as the study of the interactions between molecules in those terms. Such a view is a barrier that prevents students from understanding the high relevance of the context in chemistry. For instance, it is common that students conceive regulatory systems of pH as something alien to the solution they are regulating, something external to the solution: the multiplicity of chemical interactions involved are not usually analyzed; they are perceived as a kind of thermostat in a refrigeration system. Similar situations occur when studying solutions in states close to the saturation point, heterogeneous systems, etc., in which the importance of context is crucial. Students are exclusively anchored in the perspective of the individual, or of the form, instead of taking into account the perspective of matter or stuff, specific of chemistry.[44,45]

The distinction between simple substance and basic substance is not perceived, except in exceptional cases. Thus, it can be said that the practice and teaching of chemistry, in some sense, has brought the chemical teaching back to the conceptual framework previous to the work of Mendeleev. Our proposal (or the TBT) aims at contributing to recover the distinction between simple and basic substance, and to emphasize the importance of context in chemistry. This would help the student to become aware of the complexity of the concepts of element, compound, basic substance and simple substance.

6.2 The concept of "valence shell"

In general, the traditional approach to explain the place of elements in groups and periods of SPT is based on describing sequentially the electronic configurations by means of combinations of quantum numbers. As a consequence, the valence shell (the outermost shell of an atom, containing the electrons that can be transferred to or shared with another atom), which is the relevant notion for chemists, appears at the end of this sequential process. Therefore, students commonly direct their effort in memorizing the sequence of the diagram of construction (*Aufbau* principle, Madelung Rule), and lose sight of the importance of the valence shell. They do not interpret, for example, the reason why the sublevels *s* and *p* are "mixed" to form the valence shell of the so-called elements of the *p*-block in the SPT, among many other difficulties. Moreover, since they arrive to the valence shell after a long procedure, errors are frequent.

In the approach of the TBT based on pT's, in the 8 lateral pT's the number of electrons in the valence shell coincides with the tree number (except in tree T0 and in the complementary branches of T1 and T2). In Figure 3, it is possible to observe that, in trees 3 to 7, the number of electrons in the valence shell of the elements that make up the main and complementary branches (which in the SPT integrate the groups A and B, see next sub-section) coincides with the number of the tree. For instance, in tree T4, the elements C, Si, Ge, Sn, Ti, Zr, Pb and Hf have 4 electrons in their last shell (adding the *s* with the *p* or *d* as appropriate). Moreover, in neutral atoms the number of internal electrons can be computed by subtracting the number of electrons in the valence shell from the atomic number; so, the diagram of construction is applied only to the internal levels.[45] This strategy introduces the electronic configurations of the elements "in reverse", that is, from the valence shell to the inner shells, emphasizing the concept of valence shell, one of the most relevant in chemistry.[47] Moreover, the frequent errors in the application of the construction diagram remain confined to the inner shells, with few chemical consequences, at least at the level of teaching.

It is also important to note that TBT, based on a simple arithmetic relationship such as the triad, allows the student, once the logic of generation of triads is interpreted, to easily locate each element, by its atomic number in its corresponding pT, know the number of electrons in the valence shell, and make inferences about its chemical behavior. For example, with the logic of generation of triads, the elements of any tree can be reconstructed. And once the elements are located in the corresponding trees, it is possible to make inferences about the chemical behavior of the elements and the relationships between them; this is particularly important to relate the elements of the series A and B (see the next sub-section).

This way of introducing the concept of valence shell actually recovers Lewis's structures, with all their didactic virtues. Lewis used cubes to represent atoms, in such a way that the electrons of the valence shell in the 2nd period of the SPT are placed in the 8 vertices of the cube. The practice in the formation of the Lewis structures is particularly productive –but often underestimated– in representing chemical bond, becoming a useful resource for the student who begins the study of chemistry. In fact, this practice allows representing chemical bond in a "classical" way, with the union of 2 points, and not with a line, as currently recommended. Now, if the number of electrons in the valence shell can be obtained in the TBT without relying on electronic configurations, the student can concentrate his attention on those electrons and use Lewis's structures to analyze chemical bonds.[48]

6.3 The relations between the elements of the same groups of the series A and B

In the first tables of Mendeleev, the series A and B do not appear. In later Mendeleev's tables, those series are distinguished, with the relationships between the elements belonging to them.[49] Precisely due to the fact that the series A and B cannot be explained in quantum-mechanical terms, they have disappeared from the contemporary tables, and its use is explicitly discouraged by IUPAC.[50] However, this strategy hides important chemical analogies between elements. Some of these relationships are very relevant, and usually go unnoticed by students, especially those linking groups 2 and 3, such as the chemical similarity between Mg and Zn, and between Al and Sc. Other similarities regarding reactivity naturally arise among Ti, Si and Ge, among V, P and As, and among Cr, S and Se, among others.

The TBT based on pT's recovers the classification in series A and B in a natural way since it represents the elements the series A by the lateral branches of the pT's, and the elements of the series B –the so-called 'transition metals'– by the complementary branches of the trees. It is also interesting to notice that, in general, the elements belonging to the main branch and those of the complementary branch in a lateral tree have the same number of electrons. The exceptions of this regularity are T0, T1, and T2. However, these exceptions are the manifestations of chemical particularities of the involved elements. For instance, in T0, Pd and Pt (belonging to the complementary branch) are not very reactive, but their reactivity is a degree greater than the almost zero reactivity of noble gases (belonging to the main branch); in this way, the less reactive metals are related with the less reactive non-metals in the same tree.

6.4 Metallic elements

Traditionally, it is taught that the essential feature of transition metals is that their *d* sub-level remains incomplete; this allows explaining the variation of the periodic properties between these elements. However, this explanation produces in the student the false idea that the metallic elements are very similar to each other and even that they are "essentially equal". By contrast, the chemical differences between these elements, which are all part of the B series in the SPT, are clear within the TBT, because the transition metals appear in the different pT's that constitute the table.

Lanthanides and actinides, also known as internal transition metals, are traditionally presented as having an incomplete sub-level *f*. So, even more intensely than in the case of transition metals, students have the idea that they are all alike, an idea that persists even in advanced courses. It is true that internal transition metals are chemically very similar to each other, but ignoring their differences leads the students not noticing very chemically important elements, such as Ce, Pr, Nd, and Dy in the first series, and U, Np, and Pu in the second series, for instance. In the present proposal, although internal transition metals appear all together in the TBT, they belong to different pT's which clearly expresses their differences.

6.5 Classification of elements

The TBT provides a criterion about the relative position of the elements that are difficult to be classified, a topic currently under discussion in the studies on the foundations of the periodic system. While these topics do not appear in the teaching program, these discussions can nevertheless be interesting and informative if presented in introductory chemistry courses.

The first debate refers to the position of H and He. Hydrogen as membership of group 1 is under discussion: the question is whether it should be placed with alkaline elements or with the group of halogens in the SPT. It has also been proposed that H must appear floating on the top of the table due to its peculiarities.[51] According to TBT, the particularity of H is manifested by the fact that it belongs to the central tree, and it is the single member of its period. Nevertheless, H is connected with the rest of the TBT through its participation in two triads (0-H-He and H-F-Cl). The central position of H in TBT thus naturally manifests the importance and the multiple aspects of its chemical behavior.

In the case of helium, the discussion is whether it must be included in the group of the noble gases (for its chemical properties) or in group II with the alkaline earths (for its valence electrons). If we evaluate the question from the standpoint of the TBT there can be no doubt: He belongs to the triad He-Ne-Ar, which integrates the main branch of T0. This position characterizes He as a noble gas, in agreement with the SPT.

In addition to the positions presented, about this controversy, other alternatives have been proposed, presented with interesting arguments and discussions.[52,53,54,55,56]

Another controversy is related to the position of the elements of group 3 of the SPT. In particular, the disagreement refers to which elements have to be placed under Sc and Y: some tables place the pair La and Ac, and others the pair Lu and Lr.[57,58,59,60,61] The TBT shows that, in a certain sense, both pairs are "below" Sc and Y. This is particularly evident in the T3: Sc and Y form a triad with La; but, on the other hand, Y forms a triad with Lu and Lr (see Figure 4). In this way, the structure of trees leading to interconnected triads allows to conclude that there are good reasons for the two solutions,

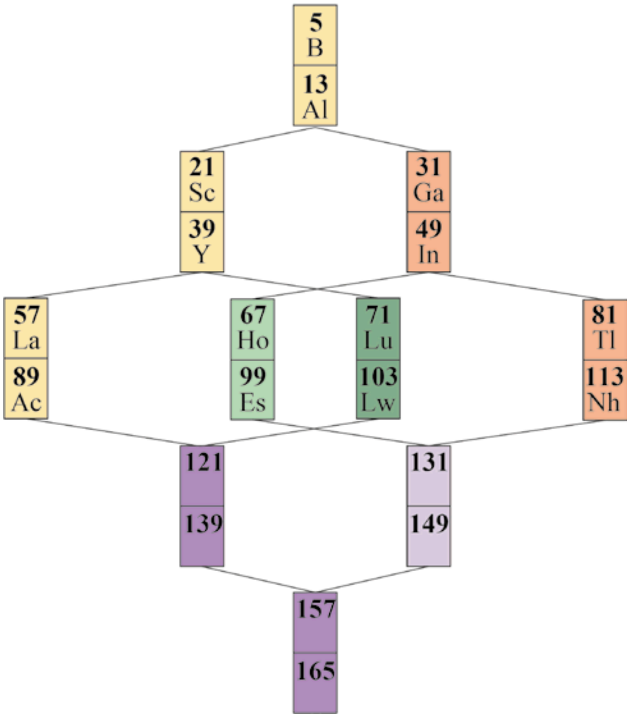

Figure 4. The periodicity tree 3.

although both are partial manifestations of a more complex relationship.

6.6 Other considerations about the foundations of the periodic system

At present, other points are debated: the existence of the element 0, the existence of a final element, and the multiplicity of possible representations, among others. Though not compulsory, a basic presentation of these topics in introductory courses might be interesting and motivational for students. It also invites them to think more deeply about the periodic system and the elements.

The TBT allows accommodating the element 0, which forms a triad with hydrogen and helium and initiates the system of triad generation. This element is conceived as an undifferentiated substance, which in a certain sense persists in all the elements: the neutron might be conceived as an empirical manifestation of the element 0. In this aspect, the TBT agrees with some recent views, such as that of Philip Stewart, who proposed a representation of the periodic system in spiral form, known as "chemical galaxy": the chemical element number zero is placed in the center of the galaxy, and its "atoms" are the neutrons.[62,63,64] The idea of element 0 sounds strange if chemical elements are considered only as simple substances, but is natural when elements are viewed also as basic substances. In the TBT, which admits the double nature of elements, the element 0 is defined in a theoretical way by following the same progression that orders all elements: it is the element with zero electrons and zero protons, and one of its manifestations as a simple substance is the neutron, which corresponds to the element with atomic number 0, mass number 1 and null electronic configuration.

Regarding the existence of a final element, a point that is left open in SPT, the proposal of TBT takes a definite position. On the basis of the conjecture that leads to the reversal of the growth trend in the central period, the periodic system has a final element with number 171. This view suggestively agrees with some very recent quantum-mechanical model.[65,66]

Finally, the TBT represents a favorable contribution to acknowledging the multiplicity of possible representations for classifications of the elements. In fact, it is based on a secondary criterion completely different from that used in the SPT, and this fact allows it to highlight different features of the classification. As Jorge Luis Borges asserts in his short story "The analytical language of John Wilkins": "… it is clear that there is no classification of the Universe not being arbitrary and full of conjectures. The reason for this is very simple: we do not know what thing the universe is."[67]

7. CONCLUSIONS AND FINAL THOUGHTS

The presentation of the periodic system in the introductory chemistry courses usually follows the teaching of the atomic structure, and the relations of periodicity among elements are based on the combination of the corresponding quantum numbers. This way of teaching often leaves out, or confines to a secondary place, the chemical perspective about elements. Moreover, as Bernadette Bensaude-Vincent stresses, Mendeleev is usually presented as a precursor of those theories, ignoring that, far from being a prophet, he was a chemist of his time, who reorganized the body of existing knowledge around the concept of element, and not around merely empirical properties of substances.[5] After describing how the historical roots of the periodic system were erased by the quantum understanding of elements and the reorganization of the periodic system through the atomic number instead of the atomic weight, this paper presents a proposal for teaching the periodic system differently, based on analyzing the chemical relationships among chemical elements on the basis of the TBT. This table, being conceived from a chemical perspective, can be a plausible option to integrate not only the study of the periodic system, but also the concepts of element, atom, molecule, mole, as well as the concepts of valence shell, chemical bond, and reactivity, among others. This novel perspective offers an approach very different from that offered by the currently predominant physical viewpoint.

Of course, the quantum mechanical perspective is nevertheless important in higher courses, and clearly it must be studied in the first courses to be able to address those challenges. However, basing teaching exclusively on the physics perspective leaves aside the chemical view of the elements, and this causes great difficulties in the understanding of many chemical topics; in this way, the perspective of classical chemistry turns out to be merely anecdotal. But this is paradoxical, especially when the objective is precisely to train professionals in chemistry. Indeed the nowadays way of teaching the classification of the elements is not only disconnected from the historical development of the periodic system, it is also disconnected from a large part of the practice of chemistry.

The TBT highlights the chemical perspective of the second half of the nineteenth century, and goes beyond the mere historical interest. That was a chemistry which, as Isabelle Stengers expressed "not only achieved its status as an autonomous science, but the science of the avant-garde, science queen, positive science model , illustrating a conception in the effective practice of pragmatic and empirical science.[41] The TBT aims to rescue that spirit, and from that position seeks to assimilate and structure the chemical knowledge about chemical elements. In particular, the aim is to recover both the individuality and the dual meaning of the concept of a chemical element, beyond of the idea of atoms and molecules as constituents of matter. On this basis, this work looks towards the future for teaching, but also, to forthcoming theoretical and empirical research in the realm of chemistry. A future full of challenges and full of difficulties, whose approach will bring us successes, but also errors, unforeseen difficulties, failures and unforeseen complications. In short, a future that is worth living.

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